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THE CEBAF PROJECT AND ITS FEW-BODY  
RESEARCH PROGRAM

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# THE CEBAF PROJECT AND ITS FEW-BODY RESEARCH PROGRAM

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## Abstract

The 4 GeV Continuous Electron Beam Accelerator Facility (CEBAF) planned to be built in Newport News, Virginia will allow detailed coincidence studies of electron and photon induced reactions on few body systems, including polarization experiments. The facility and some examples among the planned experimental program are briefly discussed.

## I. Introduction

For many years, the electromagnetic probe has been used as a precise microscope to obtain quantitative information on the structure of nucleon and nuclei. Electro- and photonuclear reactions have put strong constraints on the self consistent mean field picture of nuclei. They also gave the cleanest evidences for the role of meson currents, nucleon resonance excitation, relativistic effects and the need for introducing explicitly the internal quark structure of hadrons. It is the goal of new generation high energy and high duty factor electron accelerators like CEBAF to extend theses studies to higher energy and momentum transfer regimes in a variety of specific channels. With photon wave lengths much smaller than 0.3 fm, essential information is expected on the structure of nucleons and their resonances in nuclear matter, and on the nature of multinucleon subsystems and the strong nuclear force.

A  $\leq 4$  nucleon systems provide the best suited "nuclear laboratory" for such studies. Covering the full range of nucleon binding energies and nuclear densities they exhibit all the above mentioned effects without having the full complexity of heavier nuclei. This allows to perform completely exclusive experiments without resorting to extremely high resolution, difficult

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to achieve at high energy. Consequently, a major part of the CEBAF physics program implies d,  $^3\text{He}$ , and  $^4\text{He}$  targets. A few examples will be discussed in this talk, after a short description of the CEBAF experimental facilities.

## II. The CEBAF Experimental Facilities

The configuration of the CEBAF accelerator is sketched in Fig. 1, and its main characteristics are given in Table 1. It consists of two 0.5 GeV superconducting linacs through which the  $200\mu\text{A}$  electron beam is circulated 4 times. Microbunch separation using 2495 MHz RF deflection allows to deliver three simultaneous beams at different but correlated energies, and possibly two or more order of magnitude different intensities to the three planned end stations. The installation of a GaAs polarized electron source is being studied. A detailed description of the CEBAF project can be found in Ref. 1.

Table 1  
Main CEBAF Design Parameters

<u>Beam Characteristics</u>	Energy	0.5-4 GeV
	Average current	$200\mu\text{A}$
	Emittance	$2 \cdot 10^{-9} \pi\text{m}$
	Energy spread ( $\delta p/p$ )	$< 10^{-4}$
	Duty factor	100%
<u>Linac Parameters</u>	Type	Superconducting CW recirculating
	Frequency	1500 MHz
	Cavity design	
	Gradient	5 MeV/m
	Cavity design	
	residual Q	$3 \cdot 10^9$
	Number of cavities (klystrons)	418 (418)

Given the high duty factor and the high quality of the electron beam, preliminary designs for the experimental equipment have been performed with emphasis on coincidence experiments, and the possibility to perform high missing mass resolution measurements as well as kinematically complete multiparticle emission experiments. Consequently, two rooms (Hall A and C) will be equipped with several detection arms, mainly spectrometers, around the same pivot, while the third one (Hall B) will house a nearly  $4\pi$  detector, so-called Large Acceptance Spectrometer (LAS). The characteristics

of the detector arrangements follow from the requirements of a set of typical experiments.

The kinematical domain accessible with 4 GeV and 6 GeV incident electrons is shown in Fig. 2 as a function of the squared four momentum transfer  $Q^2 = 4 EE' \sin^2 \theta/2$  and the energy transfer  $\nu = E - E' = (W^2 - M_T^2 + Q^2)/2M_T$ , where  $M_T$  and  $W$  are the target mass and the total invariant mass of the final state. Fig. 3 shows the conditions needed to perform transverse/longitudinal separations by varying the virtual photon polarization parameter  $\epsilon = (1 + 2 \vec{q}^2/Q^2 \tan^2 \theta/2)^{-1}$ . One notices that the possibility to reach very forward angles,  $10^\circ$  or below, is essential, for both the electron and the hadron arms, the latter being often in the direction of  $\vec{q}$  at high momentum transfer.

One of the most stringent requirement is the missing mass resolution needed i) when final bound nuclear states have to be isolated or ii) when signal/noise (true/accidental) ratio has to be optimized in fully exclusive experiments dealing with very low cross sections. Hall A is designed for such experiments -- mainly  $(e, e'p)$  and  $(e, e'K)$  reactions -- while Hall C will be better suited for moderate ( $\sim 10$  MeV) resolution experiments.

The main parameters for the preliminary spectrometer designs are listed in Table 2. The layout of Hall A electron spectrometer is shown in Fig. 4. Like Hall A hadron and Hall C electron spectrometer, it is planned to make use of a few modular magnetic elements (one type of homogeneous field, rectangular, superconducting dipole, and two types of superconducting  $\cos 2\theta$  quadrupoles, with higher order correcting coils). The configuration chosen for Hall A, with one horizontal and one vertical spectrometer, allow extended target operations while optimizing acceptances and costs. Initial plan for Hall C (Fig. 5) includes two non-focusing hadron spectrometers (each of them consisting in a single dipole). The possibility to use non-magnetic devices in direct view of the target, like arrays of scintillation and lead glass counters allowing to detect neutrals, is being investigated. The Large Acceptance Spectrometer in Hall B (Fig. 6) has been designed for photonuclear and low luminosity ( $\lesssim 10^{-28} \text{ cm}^{-2} \text{ s}^{-1}$ ) electronuclear studies. Fully instrumented, it will allow multiparticle detection and identification within  $\sim 80\%$  of  $4\pi$  ( $15^\circ$  minimum forward angle) and 0.1 to 3 GeV/c in momentum.

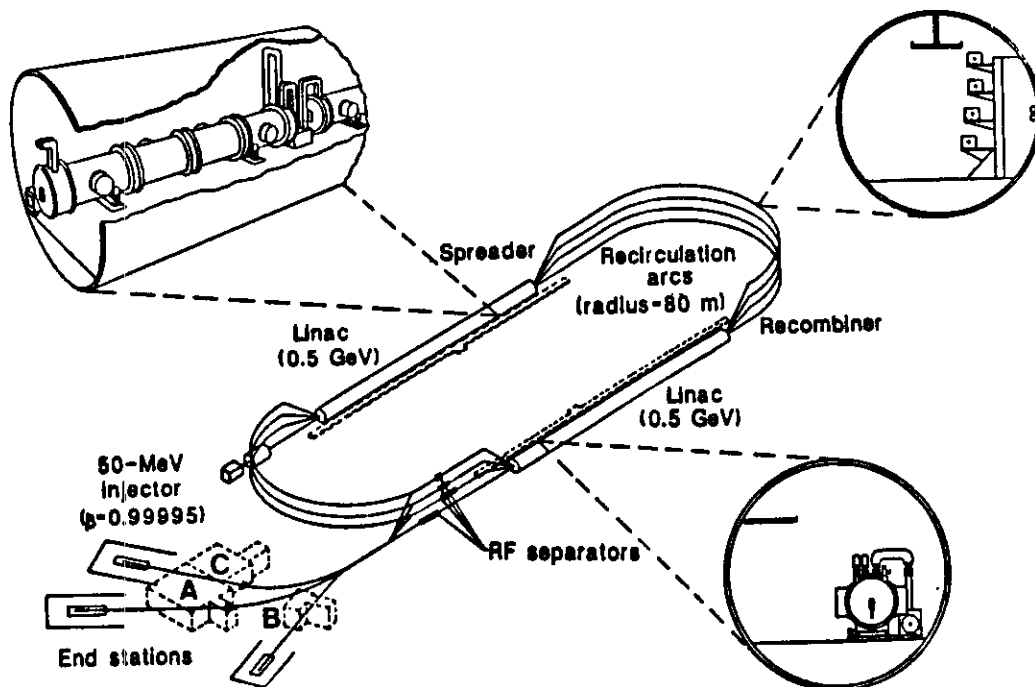


Fig. 1 Sketch of CEBAF accelerator configuration

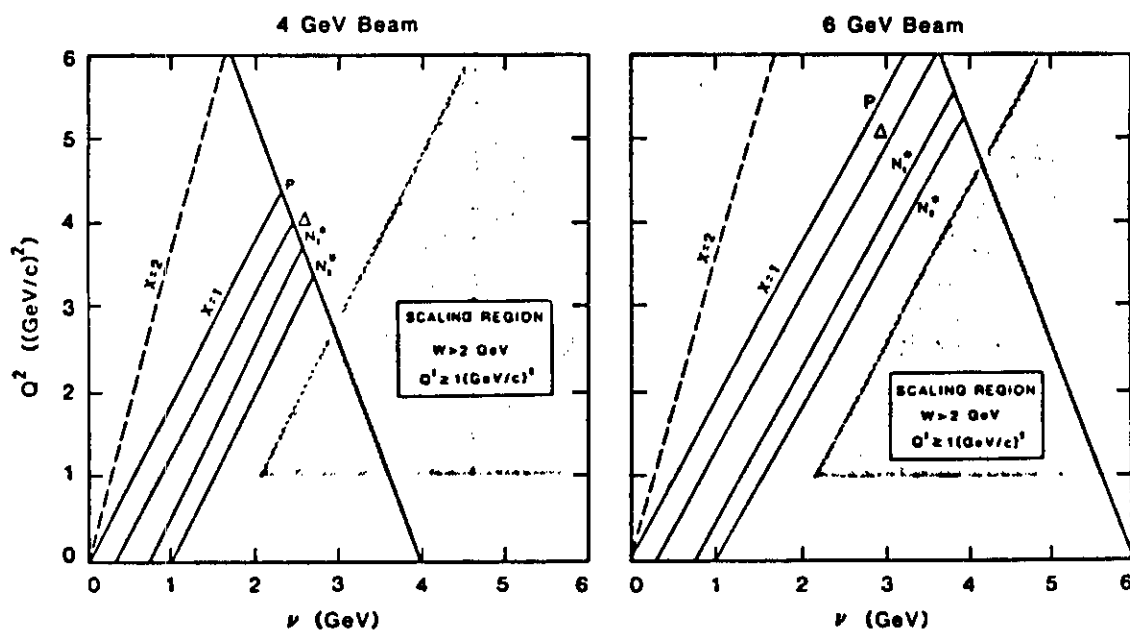


Fig. 2 Accessible regions of the  $(Q^2, \nu)$  plane. The left part of each figure corresponds to  $\sigma_{\text{Mott}} > 10^{-2} \mu\text{b.sr}^{-1}$ .

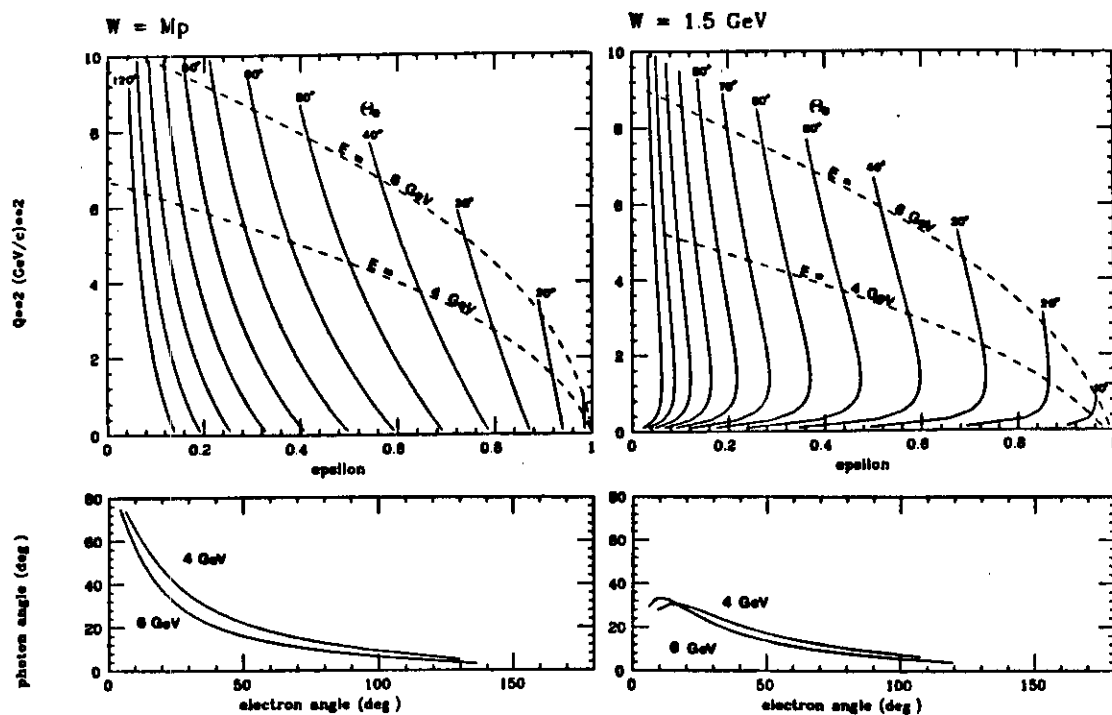


Fig. 3 Kinematical constraints for longitudinal/transverse separations in elastic and inelastic ep scattering.

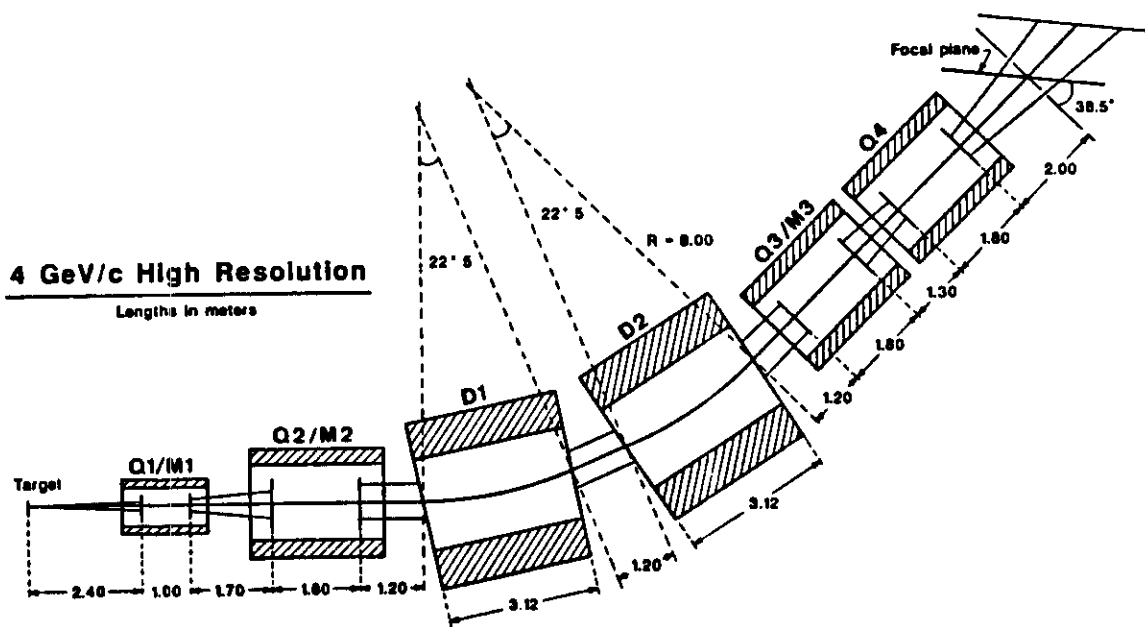


Fig. 4 Sketch of the CEBAF High Resolution Electron Spectrometer (Hall A).

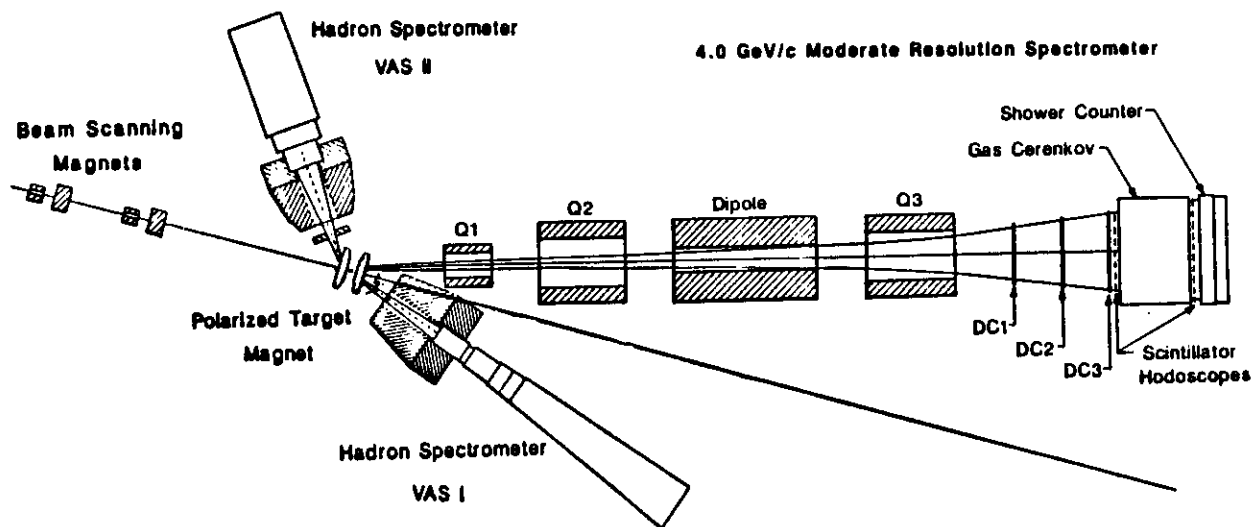


Fig. 5 Spectrometer arrangement in Hall C.

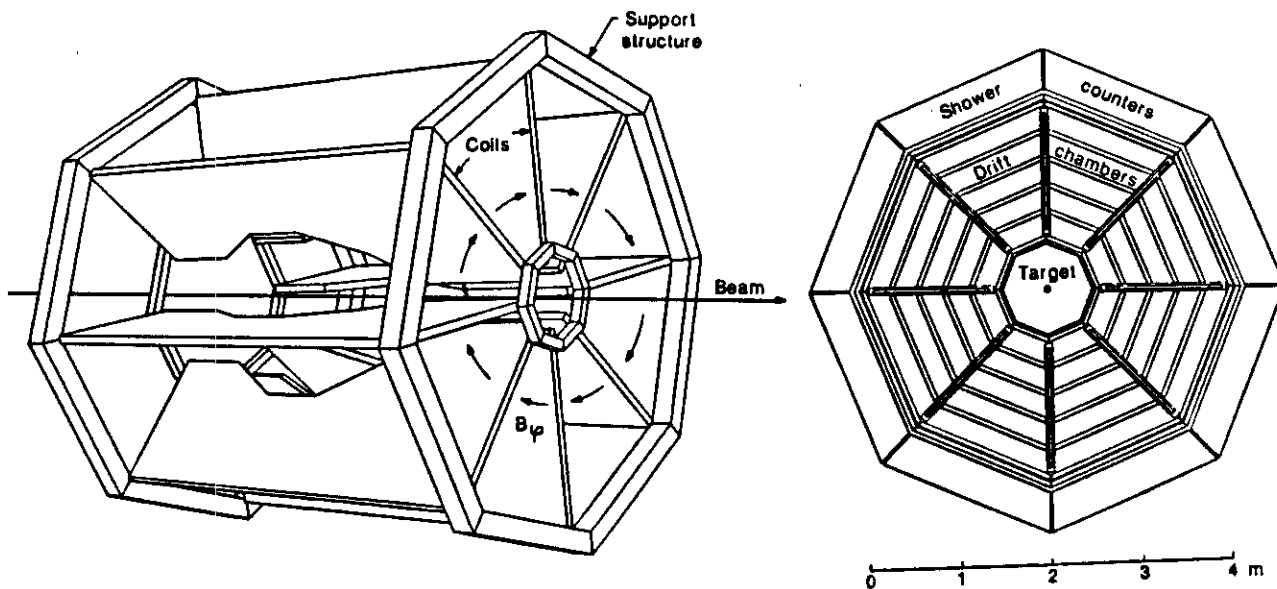


Fig. 6 Sketch of the Large Acceptance Toroidal Spectrometer

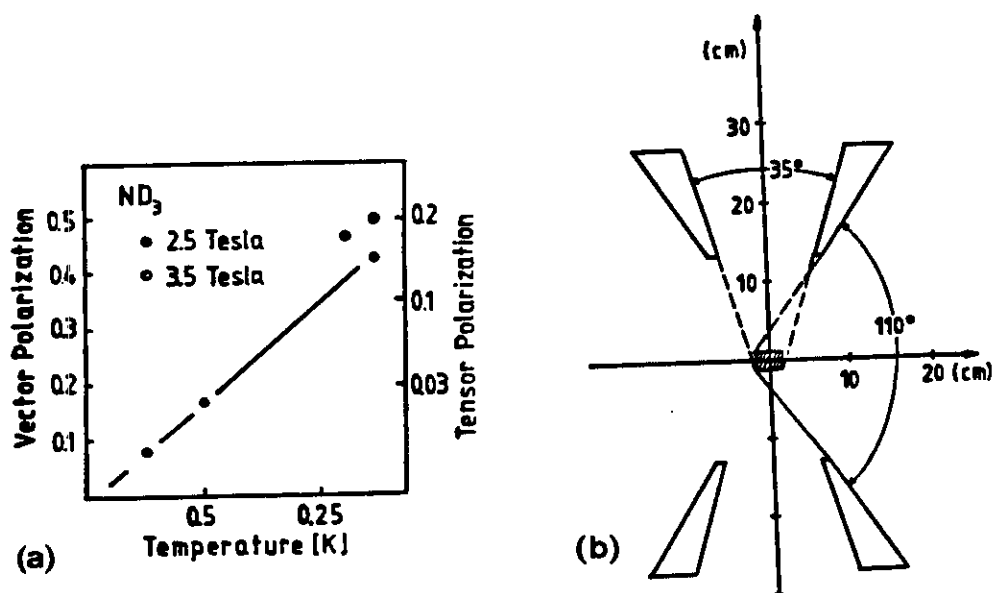


Fig. 7 Solid state polarized ND<sub>3</sub> Targets: a) deuteron polarization<sup>[2]</sup>  
b) coil geometry for CEBAF beams.

Table 2  
Preliminary Designs Parameters for CEBAF Spectrometers

Type	Maximum Momentum (GeV/c)	Momentum Acceptance (%)	Momentum Resolution	Solid Angle (msr)	Angular Range
Hall A Electron	QQDDQQ horizontal	4. (6)	10	$< 10^{-4}$	11. $10^\circ + 130^\circ$
Hall A Hadron Solution I	QQDD vertical	3.	15	$< 10^{-4}$	11. $10^\circ + 160^\circ$
Hall A Hadron Solution II	QQDMD vertical	1.2	15	$\sim 3 \cdot 10^{-5}$	35. $20^\circ + 150^\circ$
Hall C electron	QQDQ	5.5	30	$\sim 3 \cdot 10^{-4}$	6.6 $10^\circ + 160^\circ$
Hall C Hadron I	Dipole (VAS I)	3.5	$> 50$	$\sim 3 \cdot 10^{-3}$	50. $16^\circ + 150^\circ$
Hall C Hadron II	Dipole (VAS II)	1.7	$> 50$	$\sim 3 \cdot 10^{-3}$	70. $25^\circ + 150^\circ$
Hall B	Large Acceptance Spectrometer		Toroidal field, max. strength 8 superconducting coils Solid Angle Momentum Resolution		1T  80% of $4\pi$ $\sim 10^{-2}$

Based on experiences at Bonn<sup>[2]</sup> and SLAC<sup>[3]</sup>, the use of polarized solid state targets in all three CEBAF end stations is being discussed. By using  $\text{NH}_3$  and  $\text{ND}_3$  as polarized target materials, one partially circumvents the low resistivity of most chemical compounds to radiation damage. Fig. 7a shows deuteron vector and tensor polarizations achieved at Bonn in various temperature and magnetic field conditions. A  $\sim 80^\circ\text{K}$ ,  $\sim 10^{17} \text{ e/cm}^2$  preirradiation has to be performed first. Careful study of the geometry of the superconducting coils producing high field is required to achieve minimum dead zone (Fig. 7b). The very good CEBAF beam emittance allows to use small target volumes. With reasonable extrapolation of existing technology, beam current up to 5nA on  $10^{23}$  deuterons/cm<sup>2</sup>  $\text{ND}_3$  targets with 0.3 tensor polarization can be achieved, leading to a figure of merit ( $L \times P^2$ ) of  $3 \cdot 10^{32}$ , even higher than currently expected internal target performances<sup>[4]</sup>.



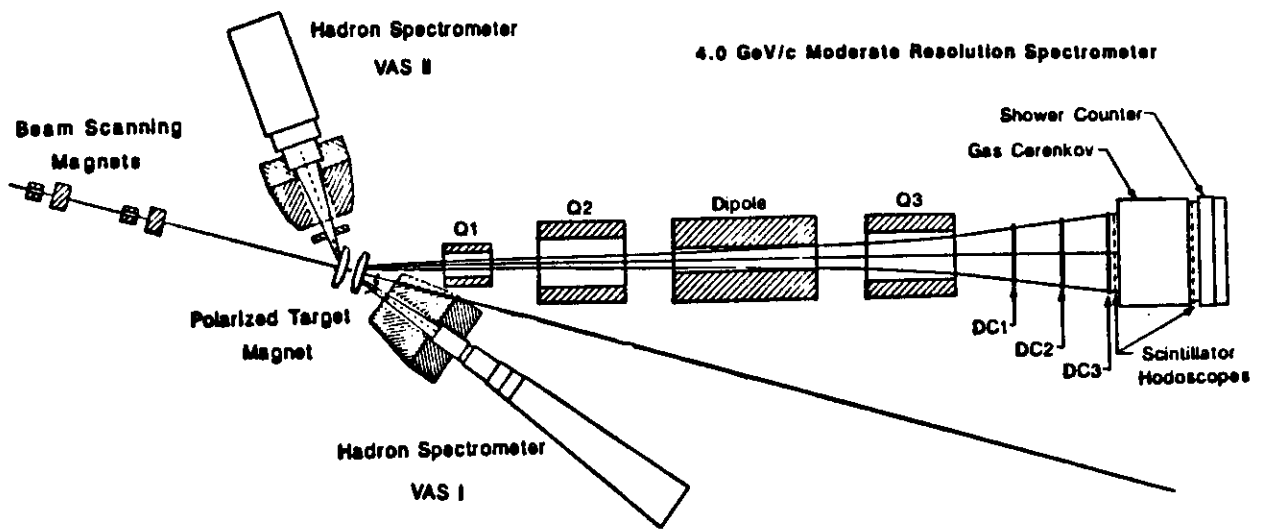


Fig. 5 Spectrometer arrangement in Hall C.

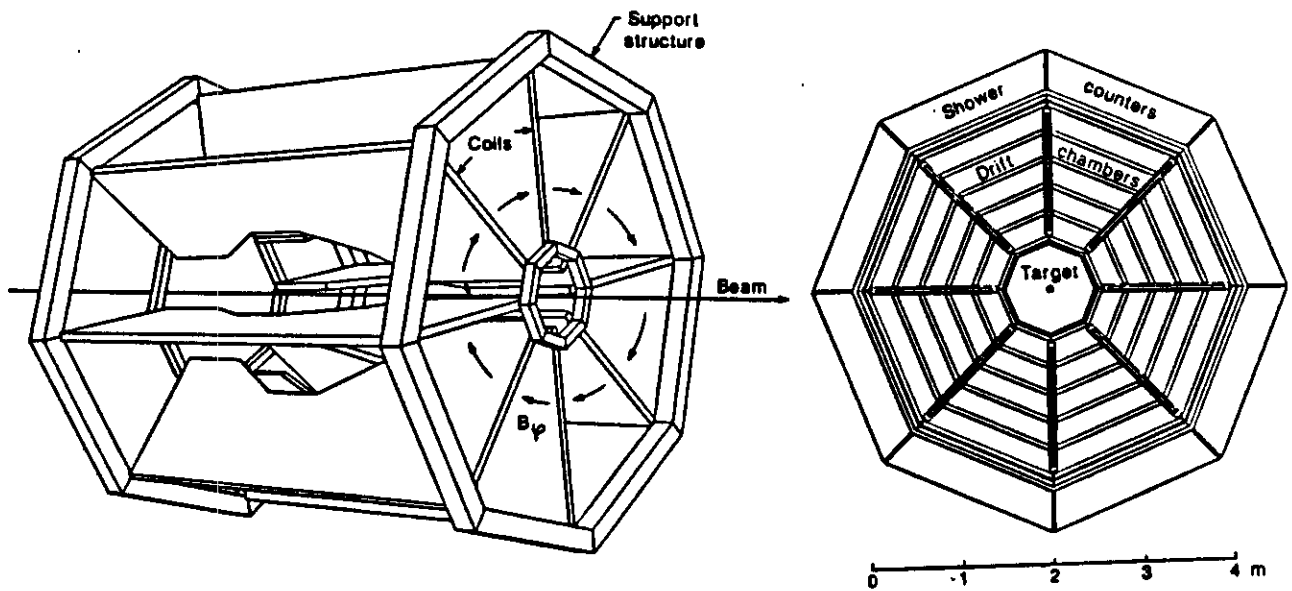


Fig. 6 Sketch of the Large Acceptance Toroidal Spectrometer

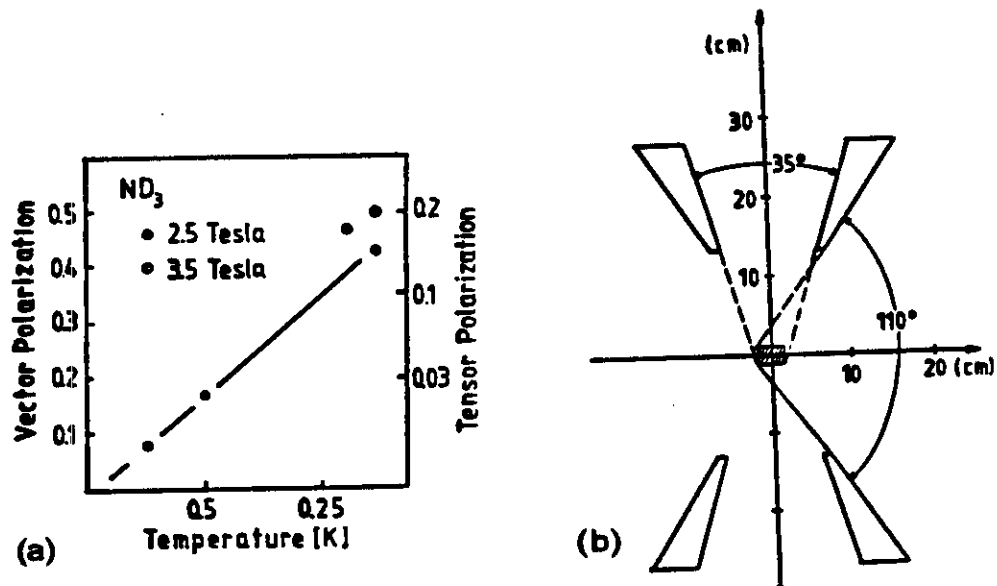


Fig. 7 Solid state polarized  $\text{ND}_3$  Targets: a) deuteron polarization<sup>[2]</sup>  
b) coil geometry for CEBAF beams.

### III. Possible Programs on Few-Body Systems at CEBAF

We describe briefly a few examples of experiments on few nucleon systems which have been discussed in the CEBAF Workshops and Summer Study Groups. A more exhaustive description of the physics possibilities can be found in the corresponding proceedings.

#### 1) (e,e'p) and (e,e'n) reactions on light nuclei

Single nucleon emission experiments, especially on light systems, will constitute an important part of the CEBAF program. In the general case of both polarized beam and target, the one-photon-exchange (Fig. 8) cross section for the (e,e'N) process provides nine invariant structure functions  $f_{ij}$ <sup>[5]</sup>, four of which appear only when the target nucleus is polarized. In principle, a measurement of these structure functions over a wide kinematical domain would give complete and basic information on the nuclear current operator. In practice, some are small, and need out-of-plane experiments to be extracted.

The simplest case is the  $d(e,e'p)n$  process. Data for the full cross section are available up to  $|\vec{n}| \sim 350$  MeV/c<sup>[6]</sup> in the quasielastic regime, and up to 500 MeV/c in a kinematical region where mesonic currents and isobar configurations give important contributions<sup>[7]</sup>. Much richer information could be obtained from the separated structure functions, as they exhibit different sensitivities to final state interactions and non-nucleonic degrees of freedom<sup>[8]</sup>. The longitudinal one, almost not affected by meson currents and  $\Delta$ 's, is the best suited for studying high momentum components and short range effects. Its separation should be achievable at CEBAF up to  $|\vec{n}| \sim 500$  MeV/c and  $Q^2 \sim 1$  (GeV/c)<sup>2</sup> with better than 10% accuracy<sup>[9]</sup>. Few coincidence data are available at higher (np) relative energies<sup>[10]</sup>, and more systematic and accurate ones would be highly desirable.

For three-nucleon systems, in which the one-body spectral function can be computed, the two isospin components  $T = 0$  and  $T = 1$  of the residual pair can be isolated by measuring the (e,e'p) cross section in both <sup>3</sup>He and <sup>3</sup>H, or the (e,e'p) and (e,e'n) cross sections on a single isotope. Extending the existing measurements<sup>[11,12]</sup> to higher recoil momenta where D-state contributions dominate may give unique information on 3-body forces, provided the measurements are performed at large momentum transfer<sup>[13]</sup>.

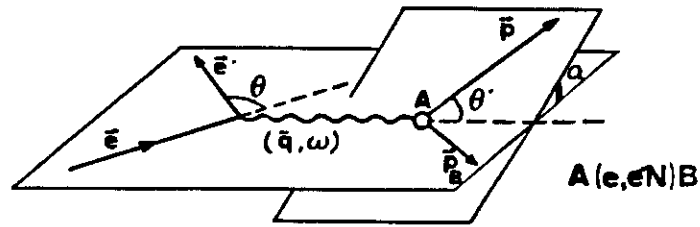


Fig. 8 Kinematics of the  $A(e,e'N)B$  process

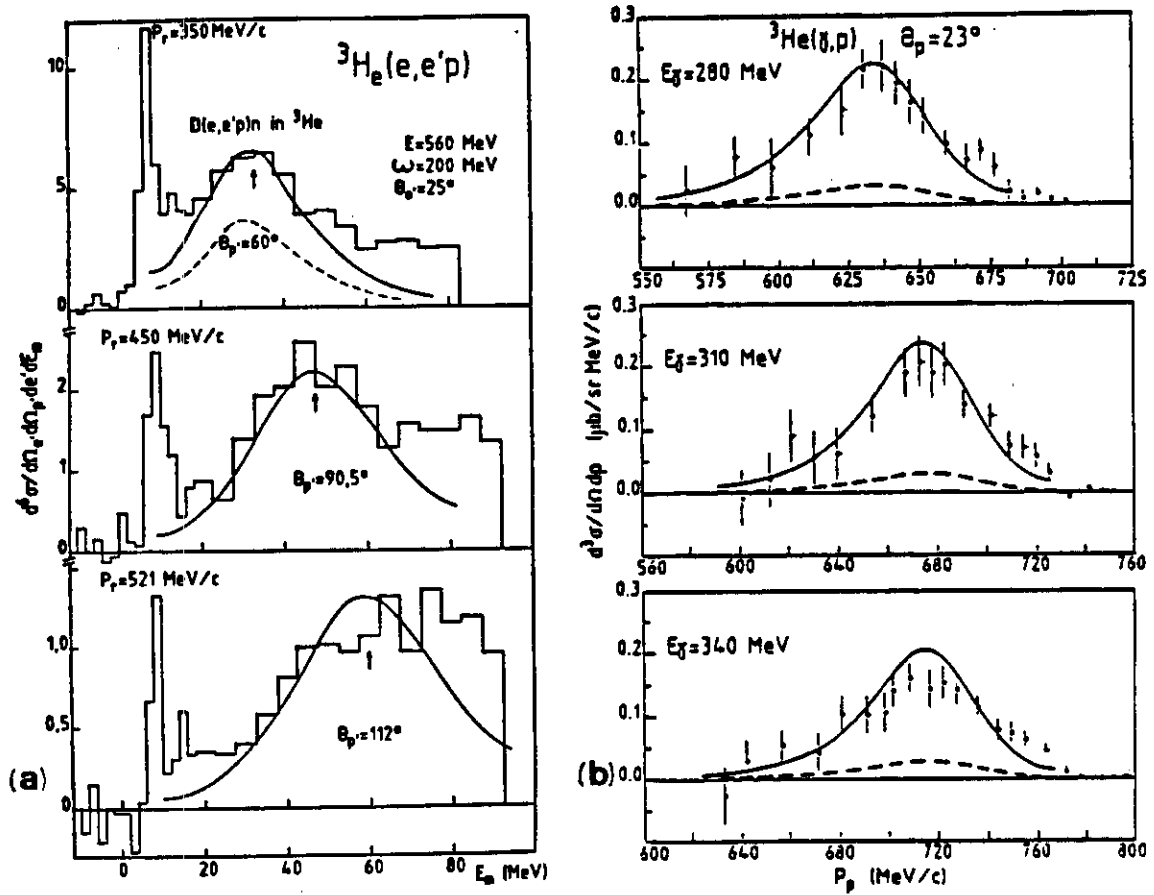


Fig. 9  $^3\text{He}(e,e'p)np$  results (a) and  $^3\text{He}(\gamma,p)np$  results (b) from Saclay<sup>[16,17]</sup> compared to Laget's calculation including (full curves) or not (dashed curves) pion exchange and FSI.

The  $(e,e'p)$  reaction can also be used to investigate how the elementary  $eN$  interaction is modified when the nucleon is embedded in the nuclear medium. Although single arm quasielastic scattering data<sup>[14]</sup> and recent  $(e,e'p)$  experiments<sup>[15]</sup> may indicate some modification in the nucleon electromagnetic properties in nuclei, this point is still controversial, and more detailed studies are clearly needed. Counting rate estimates for the  ${}^4\text{He}(e,e'p){}^3\text{H}$  reaction under appropriate kinematics show that momentum transfers up to  $Q^2 = 2(\text{GeV}/c)^2$  can possibly be achieved.

## 2) $(e,e'2N)$ reactions

The cleanest evidence for two-nucleon correlations is, at present, the spectrum of protons emitted in the continuum of the reactions  ${}^3\text{He}(e,e'p)X$ <sup>[16]</sup> and  ${}^3\text{He}(\gamma,p)X$ <sup>[17]</sup> recently measured at Saclay (Fig. 9). However, separate determination of the longitudinal cross section, allowing to eliminate MEC and  $\Delta$  contributions, is still lacking. The most promising way to study correlations is the  $(e,e'2p)$  reaction<sup>[18]</sup>. Selection rules strongly suppress two-body currents in the transverse cross section, as the  $2p$  system has no dipole moment to couple with the photon. Possible 3-body currents may then show up in the  ${}^3\text{He}(e,e'2p)n$  reaction. The longitudinal part is best suited for a detailed study of the two-body correlations. Counting rate estimates under CEBAF conditions have shown the feasibility of the experiment although a longitudinal/transverse separation would be very difficult to achieve. Moreover, the use of three spectrometers would lead to important constraints on the kinematical choices. Use of non magnetic, large solid angle devices as well as a broad survey of two-nucleon emission processes using the LAS may be an appropriate way of starting this program.

## 3) Nucleon and deuteron form factors

Precise knowledge of  $G_E^N(q^2)$  is of fundamental importance for testing microscopic models of the nucleon, as well as for quantitative analysis of most high  $Q^2$  electron scattering data. Attempts to measure it by Rosenbluth separation in quasielastic  $e + d$  scattering, or extract it from elastic  $e + d$  scattering, gives inaccurate or uncertain answers beyond  $Q^2 \sim 0.5 (\text{GeV}/c)^2$  (Fig. 10a). Measuring the recoil neutron polarization in quasifree  $d(e,e'n)p$  reactions with polarized electrons<sup>[19]</sup> is hampered by

poor and badly known efficiency of neutron polarimeters. Quasielastic scattering of polarized electrons on neutrons with spin oriented in the scattering plane, perpendicular to the direction of  $\vec{q}$  (from a vector polarized deuteron target) is being considered for CEBAF. The polarized cross section writes as

$$d\sigma/d\Omega = d\sigma/d\Omega|_{\text{unpol}} [1 + p_e p_n A^n(Q^2)] \text{ with } A^n(Q^2) \ll 2G_E^n G_M^n$$

$p_e$  and  $p_n$  being the electron and neutron polarization. With realistic figures on achievable polarizations and luminosities, measurements of  $G_E^n$  for  $Q^2$  up to  $\sim 1.5 \text{ (GeV/c)}^2$  seem feasible, with  $\delta A = \pm 0.02$  accuracy (Fig. 10b).

The separation of charge  $G_C(Q^2)$  and quadrupole  $G_Q(Q^2)$  deuteron form factors requires also polarization experiments. These form factors are very sensitive to short range effects and possible 6-quark contributions in the deuteron wave function (Fig. 11a). It has been proposed<sup>[19]</sup> to measure the recoil deuteron tensor polarization  $t_{20}$  in unpolarized ed scattering, and such experiments are underway<sup>[20]</sup>. An alternative method being investigated for CEBAF is to use a tensor polarized deuteron ( $\text{ND}_2$ ) target. In combination with  $A(Q^2)$  and  $B(Q^2)$ , the measurement of ratios  $R_i = \sigma_i(\text{pol.})/\sigma_o(\text{unpol.})$  for various target orientations enable separation of all 3 form factors. At CEBAF energies, measurements of  $R_{||}$  (target spin aligned parallel to the virtual photon) with an accuracy of  $\delta R = \pm 0.1$  for  $Q^2$  up to  $\sim 2 \text{ (GeV/c)}^2$  appear feasible (Fig. 11b).

#### 4) $(e, e' p \pi^-)$ and $(\gamma, p \pi^-)$ reactions in light nuclei

When the total center of mass energy  $W_{N\pi}$  of the final  $N\pi$  pair is around the  $\Delta$  mass, these reactions provide the most direct way of studying  $\Delta$  production and propagation in nuclear medium, and are expected to play a significant role in the CEBAF physics program. To my knowledge, the only experimental work attempted until now was the study of reactions  $^2\text{H}(\gamma, p \pi^-)p$  and  $^2\text{H}(\gamma, pp) \pi^-$  performed at Saclay<sup>[22]</sup>. Although limited in accuracy by the low ( $\sim 1\%$ ) beam duty factor, the data (Fig. 12) show significant deviations from a pure quasifree process<sup>[23]</sup>. Using virtual photons, both  $Q^2$  and the outgoing  $\Delta$  kinematics can be varied. Feasibility studies under CEBAF Hall C spectrometer conditions<sup>[24]</sup> show (Table 3) coincidence rates of  $\sim 10^3/\text{hr}$  for the reaction  $^4\text{He}(e, e' p \pi^-)x$  with  $20\mu\text{A}$  beam on  $0.2\text{gm/cm}^2$  target. A possible program could include

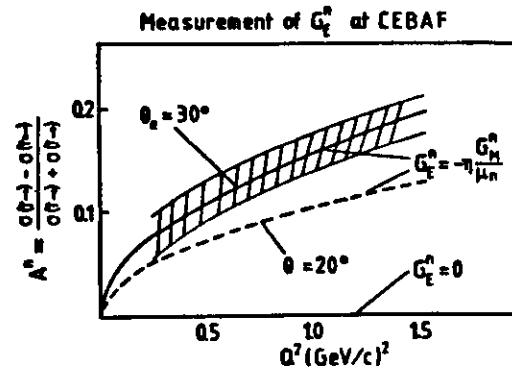
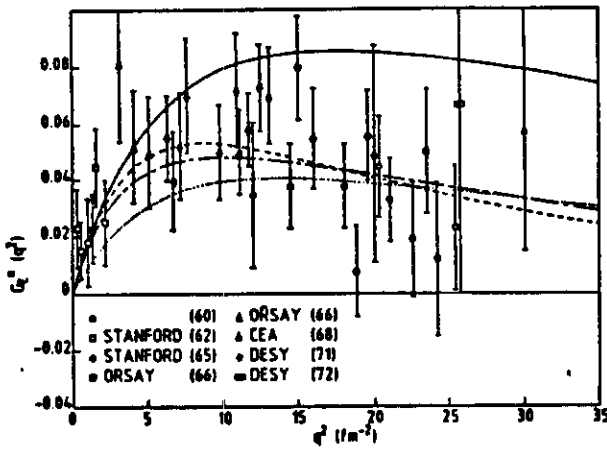


Fig. 10 Neutron electric form factor  $G_E^n$  (a) present status (b) achievable accuracy in CEBAF asymmetry measurement.

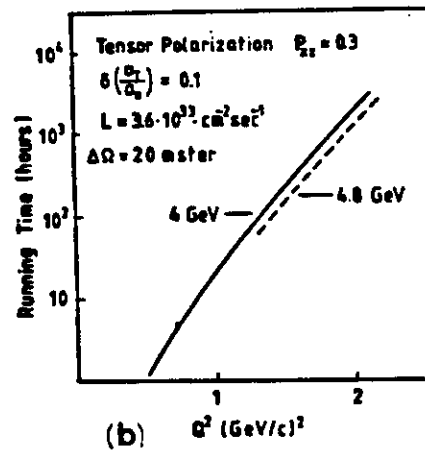
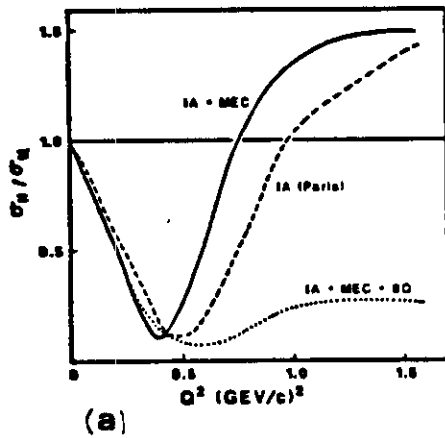


Fig. 11 Ratio  $R = \sigma_{pol} / \sigma_{unpol}$  for elastic ed scattering: (a) theoretical predictions, including  $\delta$ -quark effect<sup>[21]</sup> (b) expected running time for 10% accuracy on R.

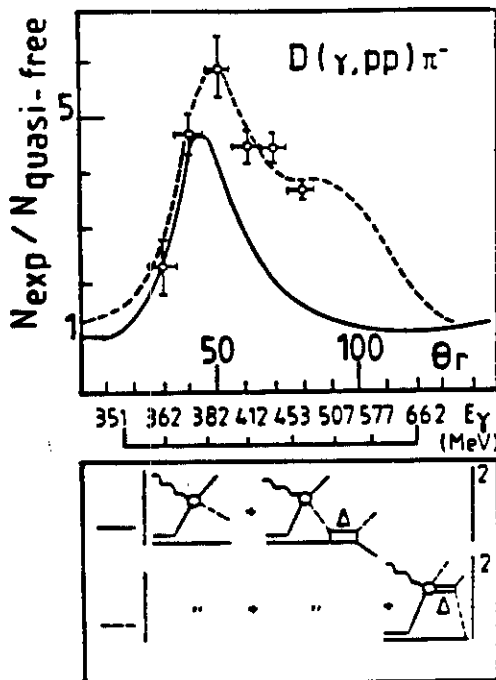


Fig. 12

Ratio of measured yield for the  $\gamma d \rightarrow pp\pi^-$  reaction<sup>[22]</sup> to the one-nucleon quasifree contribution. Solid curve includes  $\pi N$  rescattering, dashed curve includes also  $2\pi$  production mechanisms.

longitudinal/transverse separation at the  $\Delta$  peak at fixed  $Q^2 = 0.3 \text{ (GeV/c)}^2$ ,  $\Delta$  form factor in the range  $Q^2 = 0.3 - 1$  at fixed  $\epsilon \sim 0.95$  ( $\theta_e = 15^\circ$ ),  $\Delta$  angular distributions for fixed initial nucleon momentum  $\vec{p}_i$  as well as  $\Delta$ -production at high  $\vec{p}_i$ . Similar studies can be attempted on higher resonances, although multipion emission, competing strongly above the  $\Delta$ , could make the LAS in Hall B a better suited detection device. The search for resonances which decouple from the  $\pi N$ -channel (and therefore cannot be detected in inelastic  $\pi N$  scattering) would be an important test for QCD inspired models<sup>[25]</sup>.

Table 3  
 ${}^4\text{He}(e,e'p\pi^-)$  coincidence rates at  $Q^2 = 0.3 \text{ (GeV/c)}^2$   
and  $W_{p\pi} = 1.23 \text{ GeV}$  (from Ref. 24)

E (GeV)	$\theta_e$	$\Gamma$ ( $\text{GeV}^{-1}\text{sr}^{-1}$ )	$N(p\pi)$ ( $\text{hr}^{-1}$ )
2	$18^\circ$	4	$0.8 \times 10^8$
2.5	$14^\circ$	6	$1.3 \times 10^8$
3	$12^\circ$	10	$2 \times 10^8$
3.5	$10^\circ$	14	$3 \times 10^8$

##### 5) Parity experiments

Among the weak interaction experiments which may be relevant to CEBAF, the measurement of parity-violating asymmetries in elastic and inelastic ep and ed scattering are the most challenging ones. They provide basic tests of the standard model of electroweak interactions, through the predicted relationship between hadronic neutral and charge changing weak currents and electromagnetic currents through a unique quantity,  $\sin^2\theta_W$ . Experiments on the nucleon<sup>[26]</sup> would consist of measuring the asymmetry  $A = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$  for longitudinally polarized electrons. Like the previous SLAC-Yale experiment<sup>[27]</sup>, both elastic  $ep \rightarrow ep$  and inelastic  $ep \rightarrow e\Delta^+$  reactions, which have large cross sections in the range  $0.1 \leq Q^2 \leq 1 \text{ (GeV/c)}^2$  relevant to CEBAF, will determine different combinations of the coupling constants of the standard model. In this domain  $A \sim 10^{-5} - 10^{-4}$  should be measured with an accuracy of  $\delta A \sim 10^{-7}$  to  $10^{-5}$  for a substantial improvement over previous results. Other relationships between the isoscalar currents appearing in hadronic neutral weak currents and the isoscalar part of the electromagnetic current can be tested using  $ed \rightarrow ed$  and  $ed \rightarrow e(np, {}^1S_0)$  reactions as  $\Delta T = 0$  and  $\Delta T = 1$

isospin filters<sup>[28]</sup>. Although extremely difficult and time consuming, these experiments constitute an exciting challenge for CEBAF.

### Conclusion

The advent of high energy continuous wave electron beam accelerators opens new fields of investigation in electromagnetic and electroweak interaction studies on few body systems.

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